Quantifying Effects of Mid-Frequency Sonar Transmissions on Fish and Whale Behavior

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LONG-TERM GOALS

There are two high-level goals: to understand and quantify effects of mid-frequency (MF) sonar on fish and whale behavior through direct observation, and to investigate the potential usefulness of MF sonar in acoustic measurements of fish, including stock assessments.

OBJECTIVES

The initial objectives are to prove the usefulness of the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar for observing fish in the water column, and to establish protocols for calibrating the difference-frequency band of this sonar. The TOPAS parametric sonar will then be used as a mid-frequency (MF) sound source, with the aim of collecting data on herring *in situ* in the Norwegian Sea and *ex situ* in pens at the Austevoll Aquaculture Research Station. The data will be analyzed to determine possible behavioral responses of herring to MF sonar transmissions. Ultimately it is the aim to integrate acoustic data on herring with independently collected tagging data from whales to quantify behavioral effects of MF sonar.

APPROACH

This project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting a series of sound-exposure experiments at sea to observe the behavioral response of whales and Atlantic herring (*Clupea harengus*) to mid-frequency (MF) sonar transmissions. The sources of the MF sonar signals are the new, Norwegian, Nansen-class frigate sonar, with operating band 1-8 kHz, and the Kongsberg TOPAS PS18 sub-bottom profiling parametric sonar, with primary frequency band 15-21 kHz and difference-frequency band 0.5-6 kHz. The IMR project is entitled "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS.

The approach is intended to augment the Norwegian LowFreq Project in a number of ways. These are arranged by task.

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Task 1. Observation of herring by parametric sonar. The PI, K. Foote, is participating on cruises with Norwegian research vessels to observe Norwegian spring-spawning herring *in situ*, especially during the wintering period off the northwest coast of Norway. The first aim of this work is to establish the acoustic detectability of herring with the TOPAS parametric sonar difference-frequency band, which was proposed by the PI to IMR colleagues in 2003. Given measureable echoes, the second aim is to establish the quantifiability of herring by the same difference-frequency band, including measurement of numerical density and sizing based on excitation of swimbladder resonance. The PI will participate in analyses of the data, especially through application of calibration data (Task 2) and developed range compensation functions (Task 3).

Task 2. Development of standard-target calibration protocols for parametric sonar. The PI will lead development of these protocols, already commenced through the design of a standard target for calibration of the difference-frequency band of TOPAS, namely a 280-mm-diameter solid sphere of aluminum alloy (Foote et al. 2007). It is noted that measurement of fish in the upper water column will be made in the TOPAS nearfield, where the difference-frequency wave is being formed, hence the calibration measurements will be made at several ranges. In addition, the high directionality of the difference-frequency wave will require precise target positioning in the transducer beam, which can be accomplished by using an auxiliary sonar operating at an ultrasonic frequency. The PI will participate in the initial calibration trials in the Norwegian Sea, and participate in the analysis of forthcoming data, providing necessary guidelines.

Task 3. Development of range compensation functions for parametric sonar. Range compensation refers to the process whereby the range dependence of echoes, due to geometrical and absorption effects, is removed so that the resulting quantity depends only on the acoustic properties of the targets and their position in the transmit and receive beams of the observing sonar. The PI will develop range compensation functions, called time-varied gain (TVG) functions when applied electronically (Medwin and Clay 1998), for use in measuring the target strength (TS) of resolvable single targets and the volume backscattering strength (S_v) of dense layers of targets, hence of herring in states of relative dispersion and dense aggregation, respectively. For conventional sonars, two range compensation functions are particularly useful. For TS measurements, the echo strength in the logarithmic domain is increased by adding the quantity $40 \log r + 2\alpha r$, where r is the target range, typically expressed in meters, and α is the absorption coefficient, typically expressed in decibels per meter. For S_v measurements, the echo strength is increased by adding the quantity $20 \log r + 2\alpha r$. The situation is more complicated for sonars in which measurements are made in the nearfield of the transmit array. This is the case for the TOPAS parametric sonar when applied to fish in the upper water column, for the difference-frequency signal is literally being formed at ranges where backscattering is being measured. It is noted that significant TOPAS echoes are invariably received in the farfield of the transducer array used for reception.

Task 4. Use of parametric sonar as a sound source in the MF sonar band. The PI will participate in cruises to observe the behavior of herring *in situ* during the wintering period and *ex situ* in pens to determine the possible presence and magnitude of effects due to the exposure of the herring to MF sound generated by the TOPAS parametric sonar. The PI will participate in analyses of the *in situ* data.

Task 5. Integration of parametric sonar data on herring behavior with other sound exposure data on herring and whale behavior. When other sound-exposure data become available, the PI will participate in the integration of the TOPAS parametric sonar data in an assessment of the overall effects of MF

sound on fish and whale behavior. The other sound-exposure data are expected to include measurements made with the new, Norwegian frigate sonar, and observations derived from tags attached to whales in areas where the whales are feeding on fish.

WORK COMPLETED

Task 3: Quantitative application of parametric sonars requires range compensation of measured echoes, as well as calibration (Foote et al. 2007, 2009). This range compensation is considerably more complicated than for conventional, linearly-acting sonars. The basic reasons are (i) the character of the parametric sonar as a virtual endfire array, in which the difference-frequency field is formed by the interaction of collinearly propagating primary waves due to the inherent nonlinear properties of the medium (Westervelt 1963, Foote 2007), and (ii) the general need to make measurements in the difference-frequency nearfield. Thus, the difference-frequency field increases initially with increasing distance from the primary-wave transducer, and eventually decreases with increasing distance less rapidly than in the case of linearly-acting sonars. The exact behavior of this field, which has been determined previously (Foote 2009) by means of the CONVOL5 algorithm (Mellen and Moffett 1978, Moffett and Mellen 1981, Moffett 2003), has now been analyzed and compared with the range dependence of linearly-acting sonars. This has involved development of a smoothing algorithm. Results of applying this to numerical evaluations of the difference-frequency nearfield for the Kongsberg TOPAS sub-bottom profiling sonar (Dybedal 1993), with primary frequencies in the band 15-21 kHz and significant difference frequencies in the band 1-6 kHz, are presented below.

RESULTS

Task 3: For conventional, linearly-acting sonars, as noted above in the Approach, the range compensation function to be applied to the echo intensity from resolved single scatterers varies with range r as r^4 (Medwin and Clay 1998), ignoring the weaker range dependence due to absorption. For the same convensional sonars, but unresolved multiple scatterers, the principal range dependence is r^2 (Medwin and Clay 1998). For the TOPAS PS18 parametric sonar, the range dependence for compensating measured single-scatterer echo intensities at the difference frequency of 2 kHz is $r^{3.01}$ at 100 m, $r^{3.46}$ at 500 m, and $r^{3.63}$ at 900 m. At the difference frequency of 5 kHz, the respective single-scatterer range dependences are $r^{3.15}$, $r^{3.57}$, and $r^{3.74}$. For the same parametric sonar, the range dependence for compensating measured multiple-scatterer echo intensities at the difference frequency of 2 kHz is $r^{1.32}$ at 100 m, $r^{1.61}$ at 500 m, and $r^{1.72}$ at 900 m. At the difference frequency of 5 kHz, the respective multiple-scatterer range dependences are $r^{1.35}$, $r^{1.66}$, and $r^{1.80}$. There is convergence to the range dependences of compensation functions for conventional sonars at sufficiently large ranges. However, such ranges exceed those typically encountered when measuring fish in the water column, of order tens of meters to 500-600 m, thus requiring attention to the more complicated nearfield behavior of the difference-frequency band of the parametric sonar. General expressions for the parametric sonar range compensation function are now published together with numerical evaluations of the difference-frequency nearfield for the mentioned particular parametric sonar (Foote 2012).

IMPACT/APPLICATIONS

National Security

Navy operations at sea can be affected by the presence of marine mammals. It is expected that the results of the project will contribute to knowledge of possible effects of MF sonar transmissions on the behavior of whales as well as that of other marine animals, especially including fish.

Economic Development
More general use of MF sonars encompassing both water-column and sub-bottom domains may encourage the application, hence increased production, of such sonars. Parametric sonars are especially attractive in this regard because of their physical compactness relative to the exceptionally narrow beamwidths that they produce at low frequencies.

Quality of Life
Society is concerned about the impact of sonar on marine life. This project is attempting to learn about this impact in a quantitative way, ultimately so that possible adverse effects can be avoided or otherwise mitigated.

Science Education and Communication
Forthcoming results from this project are already being published through the scientific literature and lectures to the public. It is expected that these and other publication and communication activities will contribute to science education, as through academic programs in marine science, as well as to more general science literacy among the interested public.

RELATED PROJECTS

As mentioned in the approach section above, this project represents a collaboration with the Institute of Marine Research (IMR), Bergen, Norway, which is conducting the project "Low frequency acoustics: potentials and dangers for marine ecosystems (LowFreq)," with funding from the Norwegian Research Council. Additional participating institutions in the LowFreq project are the Norwegian Defence Research Establishment, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution, and Kongsberg AS. It is expected that the Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the ONR project in disseminating forthcoming results.

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